TECHNICAL NOTE:

A REDESIGNED DFA MOISTURE METER

R. P. Haff, R. Young

ABSTRACT. *The DFA moisture meter has been internationally recognized as the standard for determining moisture content of dried fruit in general and is the AOAC Official Method 972.2 for measuring moisture in prunes and raisins since 1972. The device has remained virtually unchanged since its inception, with its operation based on conductance of a sample across an electrode pair that forms one branch of a Wheatstone bridge. In recent times, obtaining appropriate parts for the device has become problematic, as maintaining the original Wheatstone bridge design requires a precision potentiometer with nearly identical non-linear characteristics to the original. The design of the moisture meter has now been updated to use modern electronic components to, among other things, mimic the original potentiometer so that calibration charts, as well as AOAC certification, remain valid. The redesigned meter was compared to the original in moisture readings of raisins, prunes, and apricots. Scatter plot regression resulted in R^2 of 0.9999 and slope of 0.9902, indicating high correlation and identity between the original and modified meters. The updated device automates the time-consuming and error-prone steps currently performed manually and determines moisture content in 7 s.*

Keywords. *Moisture meter, Wheatstone bridge, DFA, Dried fruit, Potentiometer.*

The DFA moisture meter has been internationally recognized as the standard for determining moisture content of dried fruit and is the AOAC Official Method 972.2 for measuring moisture in prunes and raisins. The instrument has remained virtually unchanged since its inception and continues to be referred to as the DFA moisture meter (fig. 1).

The underlying principle of the instrument's operation correlates 60-Hz conductivity through a dried fruit sample when connected across an electrode pair (R_2 of fig. 2) of a Wheatstone bridge circuit to the moisture content. Specific details of the Wheatstone bridge circuit employed, including all resistance values, has been previously reported (AOAC, 1972). One branch of the Wheatstone bridge contains a non-linear wire-wound potentiometer (R_1) (10k Samarius p/n 55-140-020) in series with the fruit sample, while the other (reference) branch consists of a fixed resistor (R_a) and a switched tap resistance (R_b). The potentiometer is used as a variable resistor to obtain a null reading with respect to the reference branch. A microammeter measures the half-wave rectified current between the two branches and provides the operator a visual indication of the null condition. The seven position tap switch in the reference branch allows selection of various resistance values, depending on the type of sample being measured. For instance, for raisins with low moisture, a specific tap setting is indicated in the appropriate table (fig. 3). The sample is ground and packed into a cylinder which is inserted into the circuit (R_2). The potentiometer is adjusted until a null reading is obtained. Using the dial position on the potentiometer (k value, 0 to 100) for the null reading, the selected tap position, and the sample temperature, the moisture content is obtained from the table (DFA of California, 2011).

Figure 1. DFA moisture meter including meter, sample holders, thermometer, calibration cylinders, and moisture tables.

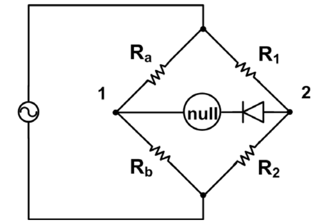

Figure 2. When the voltage across two branches of a Wheatstone bridge is null, then $V_1 = V_2$ and $R_a/R_b = R_1/R_2$. For the configuration of the moisture meter, R_a is fixed, R_b is variable and is determined by the tap setting, R_1 is the potentiometer, and R_2 is the sample.

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Table 972.20A. Conductance-temperature correlation for natural or low moisture raisins; switch setting, tap 6

%	Conductance readings at temperature (°F[a]):																							
Moisture	56	58	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96	98	100	102
9.0																9.0	15.0	21.0	25.0	29.0	33.0	36.0	39.0	42.0
9.5													4.0	11.0	17.5	22.5	27.0	32.5	37.0	40.5	44.0	47.0	49.0	51.5
10.0									1.0	7.0	13.5	17.5	23.0	28.5	34.0	38.0	41.5	45.5	49.0	52.0	54.5	57.0	59.0	61.5
10.5							7.5	13.0	18.0	24.0	29.5	35.0	40.0	44.5	49.0	51.5	54.0	57.0	60.0	62.0	64.0	66.0	68.0	70.0
11.0					8.5	16.0	22.5	28.0	34.0	39.0	44.0	48.5	53.0	56.0	59.0	61.5	64.0	66.0	68.5	70.5	72.5	73.8	75.3	76.8
11.5			9.0	18.0	26.0	31.0	36.0	42.0	47.5	51.5	55.5	58.7	62.5	64.7	67.5	69.5	71.0	73.0	75.0	76.5	78.3	79.6	81.0	82.5
12.0			23.5	30.5	37.5	42.5	47.0	52.0	56.5	60.0	63.3	66.5	69.0	71.0	73.0	74.5	76.0	78.0	79.7	81.0	82.0	83.8	85.2	86.5
12.5	16.5	27.0	34.5	40.0	46.0	50.5	55.0	59.0	63.0	65.8	68.6	71.0	73.3	75.0	76.6	78.0	79.7	81.3	82.6	84.0	85.4	86.7	88.0	89.3
13.0	30.5	37.2	42.5	48.0	52.3	56.5	60.5	64.3	67.7	70.0	72.5	74.8	76.7	78.3	79.7	81.2	82.6	83.8	85.2	86.5	87.8	89.2	90.5	91.3
13.5	40.0	45.0	49.7	54.0	58.0	61.5	65.0	68.5	71.3	73.4	75.4	77.5	79.4	80.7	82.0	83.5	85.0	86.2	87.3	88.5	89.8	91.0	92.2	93.0
14.0	48.3	52.5	56.5	60.0	63.0	66.0	69.2	72.0	74.5	76.4	78.0	80.0	81.7	83.0	84.4	85.6	87.0	88.0	89.3	90.3	91.5	92.6	93.8	94.6
14.5	55.3	59.0	62.3	65.0	67.6	70.4	72.7	75.0	77.0	78.7	80.4	82.0	83.7	85.0	86.2	87.3	88.7	89.7	90.8	91.8	93.0	94.0	95.0	95.8

Figure 3. Table used for determining moisture content from the k-value and temperature.

Twenty-four tables for various dried fruits are available. The values within each table are derived experimentally based on the dial reading of the specific non-linearity of the Samarius potentiometer. The meter's calibration is verified using cylinders of known resistance and required k null values for each tap position. While the device has proven to be extremely rugged and reliable over the years, in recent times obtaining appropriate parts for the device has become problematic, as maintaining the original Wheatstone bridge design requires a precision potentiometer with (nearly) identical non-linear characteristics to the original. In addition, manually referencing the moisture content from the tables can be time-consuming and introduces a potential source of error that could be eliminated with digital lookup tables. The objective here was to redesign the meter using modern electronic equipment without altering the underlying principles so that the AOAC accreditation would not be affected.

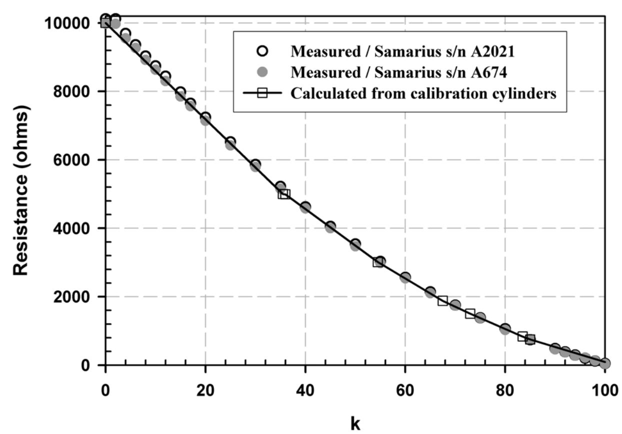

Figure 4. Calculated and measured non-linearity of the Samarius potentiometer.

Methods and Materials

Potentially time-consuming and error-prone operations of the original meter were eliminated by incorporating a programmable embedded controller with 512 K flash memory (Tern Model FB, Davis, Calif.) and a digital variable resistor. To maintain consistency with the published moisture tables it was necessary to determine the Samarius' non-linear relationship and the null resistances. From the calibration cylinders, the relationship between the potentiometer k value and the null resistance was plotted (fig. 4), and a regression formula was used to determine the required non-linearity of the potentiometer:

$$R = 0.62295k^2 - 161.97052k + 9994.16511 \quad (1)$$

$$with\, R^2 = 0.99995$$

The same relationship was plotted in figure 3 for null resistance values measured on two DFA moisture meters (s/n A2021 and s/n A674) for comparison to equation 1, yielding after regression:

$$R = 0.6758k^2 - 170.86k + 10382 \quad (2)$$

and

$$R = 0.6678k^2 - 168.68k + 10244 \quad (3)$$

Equations 1-3 are consistent with the physical fabrication of the potentiometer: wire wrapped around a trapezoid form, itself wrapped around a cylinder. Correlation between the measured and computed values of R was evaluated and found to have almost perfect positive linearity. Of course, in order to replace the potentiometer with a digital equivalent it is necessary to derive the k values from the required null resistance, so that the inverse of equation 1 is required. The inverse for a quadratic equation is well known as a variation of the quadratic formula.

The digital variable resistor consisted of 11 individual serially connected resistors, each connected with a bypass reed relay (Coto 9001, North Kingstown, RI). Relay switching was directly controlled by the controller's 11-bit digital output. Using standard 0.1% resistors with resistance values of 5120, 2560, 1280, ... 5 (Ω) provided a maximum available resistance of 10.24K Ω with 5-Ω resolution. The controller's software algorithm stepped through resistor null correction values based on proportional, integrative, and derivative null errors for a fixed time period, while saving "best" values of resistance in an array. The array of "best" null resistances was averaged to predict the most reliable null resistance value. The inverse quadratic equation was then applied to determine the appropriate k value.

The Analog-to-Digital Converter (ADC) of the controller was used to measure the low-pass filtered half-wave null signal in differential mode. A second ADC input was used to monitor the fruit sample's temperature with an integrated circuit (IC) sensor probe constructed with a precision Fahrenheit temperature sensor (National Semiconductor, model no. LM34CAZ, Santa Clara, Calif.). The controller's digital input port was used to monitor the state of the 7-tap switched resistance as well as a pair of pushbutton switches. The first switch was used to sequentially list the various types of dried fruits for which tables are available on a two-line LCD display for user selection while the second was used to initiate a measurement. The flash memory in the embedded controller was used to store the software program as well as the 24 moisture content tables. In the measurement phase, after 7 s of software execution, the k value, temperature, and moisture content were displayed on the LCD display.

The modified moisture meter was tested against the original s/n A2021 (software implemented eq. 2 inverse function) for samples ranging from 10% to 35% moisture content. The sample set consisted of raisins (11% to 20.5% moisture, 86 samples), low moisture prunes (20% to 30% moisture, 15 samples), high moisture prunes (34% to 35% moisture, 10 samples), and apricots (30% to 32% moisture, 13 samples). Linear regression was performed on the scatter plot of moisture measurements for the modified instrument versus the original and checked for both correlation and identity (slope = 1). Since the goal is to mimic the original design, the data from the A2021 meter was treated as without error, while the data from the modified instrument was considered to contain error. Under these circumstances, it is then appropriate to perform a standard regression, rather than a Deming regression, which accounts for error along both axes (Rhoads, 2010).

Results and Discussion

Of the 124 samples tested with A2021 and the new instrument, 83 yielded the same moisture content. For the remaining 41 samples, results differed between the new instrument and the old by either plus or minus 0.5%. The scatter plot and regression are shown in figure 5, with R^2 = 0.9999 and a slope of 0.9902, indicating high correlation and identity. The k values used in the charts vary along a column of fixed temperature to a degree that is large compared to the percentage of error in predicting them, i.e., the change in k value from one chart row to the next is large (fig. 3). At worst, the regression formula results in the selection of the k-value in an adjacent row to the true value, leading to a 0.5% disagreement in moisture content determination between the new meter and the old. The frequency with which this disagreement occurs is correlated with the error in matching the non-linearity curve of the potentiometer as described previously.

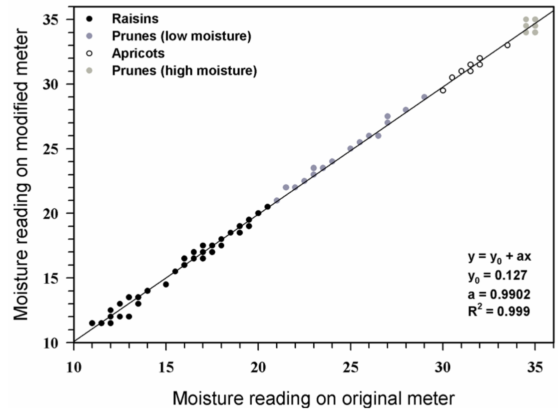

Figure 5. Scatter plot and regression for moisture content measurements between the original and modified moisture meters.

Software modifications can improve the precision of the moisture readings by extrapolating between the 0.5% intervals recorded in the standard charts. However, the design of the modified meter was intended to replicate moisture meter A2021 while maintaining its normal test procedure so as not to affect the AOAC accreditation.

Conclusion

The Wheatstone bridge design of the DFA moisture meter has been updated by using an embedded controller to perform the time-consuming and error-prone functions and by incorporating a digital variable resistor and an electronic temperature probe. All available resources on the controller board (digital in/out, ADC, 512K flash memory) are fully utilized by the software to calculate and display moisture results on an LCD display in 7 s. To maintain consistency with the published moisture tables it was necessary to determine Samarius' non-linear (the original variable resistor) relationship and the required null resistances to meet calibration requirements.

The moisture content of 124 samples consisting of raisins, apricots, and prunes were measured using the original meter and the modified meter and the results were compared. Of the 124 samples, 83 resulted in identical readings while the remaining 41 differed by 0.5%, the smallest difference between rows in the original tables. Regression of the scatter plot gave an R^2 of 0.9999 and a slope of 0.9902, indicating a high degree of correlation and identity.

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